DOI 10.5162/sensoren2024/P29

Additive Manufactured Capacitive Displacement Sensor Concept for Adaptive Pin-Array Gripper

Steffen Schröder[1], Thomas M. Wendt[1], Stefan J. Rupitsch[2]

[1]Offenburg University of Applied Sciences, Work-Life Robotics Institute, 77652 Offenburg, Germany
[2]University of Freiburg, IMTEK - Department of Microsystems Engineering, 79110 Freiburg, Germany

Abstract

This research presents a capacitive displacement sensor concept for use in a pin array gripper. The sensor measures the displacement of individual pins with a plate capacitor structure. The pin is movably positioned between the electrodes. The capacitive displacement sensor is constructed with sensing, guiding, and shielding electrodes. A homogeneous electric field is achieved between the capacitor plates to ensure a linear change in capacitance. A shielding concept for the sensor has been evaluated to minimize external interference and mutual interference between the individual displacement transducers. This ensures stable operation and reliable displacement measurements of the individual pins. The design of the concept for additive manufacturing offers advantages in terms of customization and implementation on different pin gripping systems, as well as a compact design. A test sensor was additive manufactured. The newly developed sensor was tested in an experimental setup to ensure functionality and comparing the sensory behavior with the simulations.

Keywords: Capacitive sensing, additive manufacturing, pin-array gripper.

Introduction

Robots are utilized in numerous applications due to their versatility, which makes them suitable for a wide variety of tasks. A challenge for modern gripping systems is the handling and gripping of various objects. A variety of gripping systems are available, including parallel jaw grippers, vacuum grippers, human hand grippers and pin-array grippers [1], [2]. Pin-array gripping systems consist of several individual pins that can move independently of each other and adapt to various structures [3]. These increases contact friction between the gripper jaw and the object. They withstand shear forces due to the flexibility of the pins in one direction. This distinguishes them from conventional compliant structures that deform evenly in all directions, such as foams, silicones and other soft materials.

Motivation

Adaptive pin-array gripper in robotic applications promise improved efficiency and the ability to deal with uncertainties in the positioning of objects and surface geometries. This increases versatility and adaptability to meet the demands of various tasks in different industries. Advanced sensors in gripping systems are important to ensure precise and safe handling. In [4], a vision-based approach tracks the movement of each pin and estimates the displacement. Environmental interferences, such as shadows and reflections, are disturbing factors for camera solutions. Vision systems often require special lighting and optics, which increases the size of the entire system.

Concept and working principle

The exploited sensor concept is based on a grounded parallel plate capacitor. A parallel plate capacitor is created by applying different potentials to two electrodes, generating an electric field between them. Without taking into account stray fields, the capacitance C of a plate capacitor can be calculated by

$$C = \varepsilon_0 \varepsilon_r \frac{A}{d}. \quad (1)$$

In (1), ε_0 represents the permittivity of vacuum space, ε_r the relative permittivity of the dielectric material, d the distance between the electrodes, and A the area of the sensing plate. The capacitance of a parallel plate capacitor is affected by the geometry of the electrodes, the distance between the plates, and the dielectric properties of the material. The change in dielectric properties is the basic working principle of the presented sensor design. The space between the plates consists of two different materials and can be thought of as two parallel capacitors. The current location of

DOI 10.5162/sensoren2024/P29

the pin divides the two capacitors horizontally into one containing air and the other containing the pin material. Moving the pin causes the total capacitance to change due to the changing material. Consequently, we can determine the pin position by measuring the capacitance.
COMSOL Multiphysics was used for the finite element method (FEM). The simulations were performed with polylactic acid (PLA) as pin material with an ε_r of 2.8. This value is based on the results of [5], [6].
The concept builds on previous work from [7], in which a capacitive level sensor was designed. The sensor includes sensing, shielding, guiding electrodes and a ground electrode. The ground electrode is located on the opposite side of the sensing electrode and forms the parallel plate capacitor. The sensor concept is shown in Fig. 1.

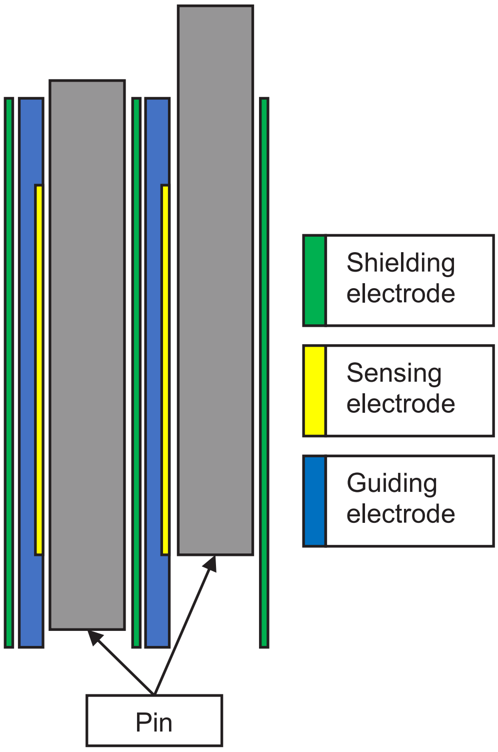

Figure 1: Displacement sensor concept for a two-pin gripper.

The electric field of the sensing electrode is directed within the measuring range and edge effects are minimized due to the arrangement of the guiding electrode. Fig. 2 shows the simulated homogeneous electric field in the relevant measuring area. Linearity, precision, and accuracy are achieved through this concept. The grounded shielding electrodes protect the sensor from external influences and prevent mutual interference between the individual pin sensors.

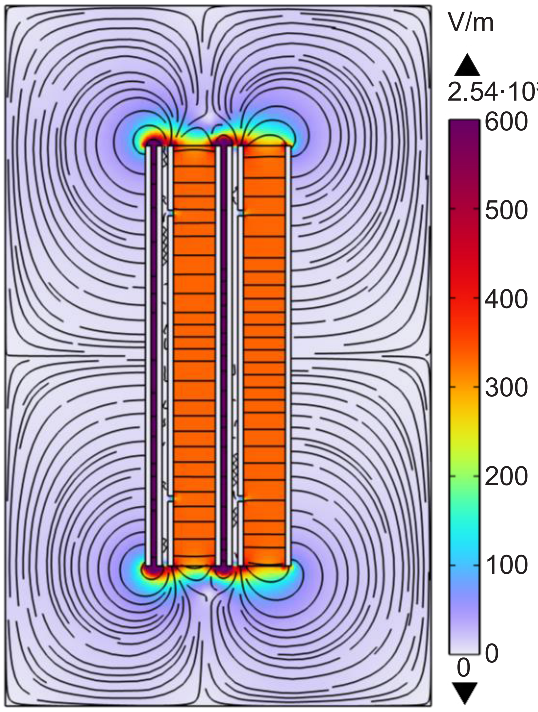

Figure 2: Simulation of the electric field for the two-pin sensor concept.

Test Sensor Design

A test sensor was designed for proof of concept. The sensor is 20 mm wide, 30 mm long and 5.4 mm thick. All electrodes have a thickness of 0.4 mm. The guiding electrode is divided into two parts i.e., guiding electrode A and B. The sensing electrode is 10 mm in width and 20 mm in length. The guiding electrode A is arranged in a U-shape around the sensing electrode. A wire is connected to the sensing electrode through a 1.4 mm notch. A thickness of 0.4 mm PLA for Carrier A and Carrier B is sufficient to isolate the electrodes. The ground electrode on the opposite side is separated from the sensing side by Carrier C. This has a recess for a pin measuring 10 mm wide by 25 mm long and 3 mm thick. The design of the test sensor is shown in Fig. 3.

Materials and Machine

The sensor was manufactured using Neotech AMT 15X SA with a layer height of 0.2 mm and 100% filling density. The 3D-printed sensor is made of PLA (ecoPLA, 3DJAKE) and conductive PLA from Proto-pasta. The conductive layers serve as electrodes.
Copper wires are applied to integrate the electrodes into the evaluation circuit. The test sensor as complete and partially with the sensing side is shown in Fig. 4.

DOI 10.5162/sensoren2024/P29

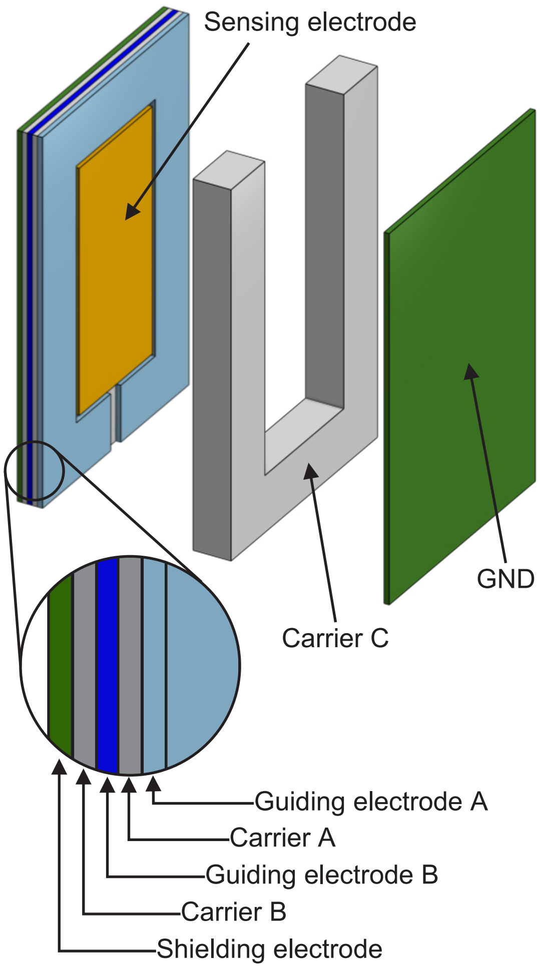

Figure 3: Design of the test sensor as partial explosion view.

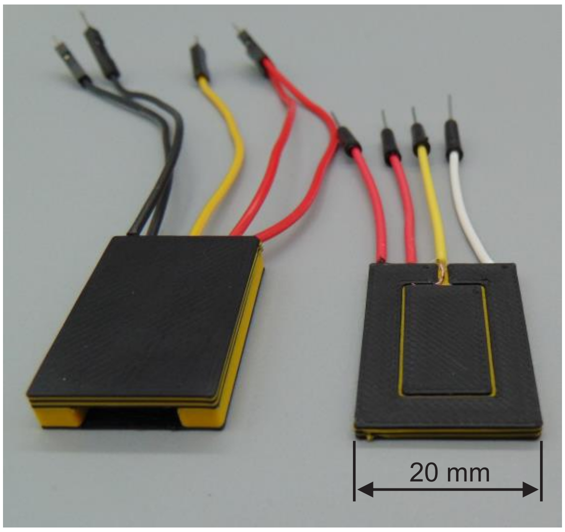

Figure 4: Additively manufactured test sensor as complete (right) and partially with only the sensing side (left).

Experimental Setup

We evaluated the test sensor in an experimental setup to verify the results of the simulations. The sensors were connected to a capacitance-to-digital converter (CDC). The capacitance measurements were performed on the EVAL-AD7747 board. This board utilizes the AD7747 CDC to measure capacitance with high accuracy (± 10 fF) and linearity (± 0.01%). The CDC has a port for active shielding connected to the guiding electrodes [8]. The evaluation board was connected to a PC where the data was collected and analyzed in MATLAB. The setup is shown in Fig. 5.

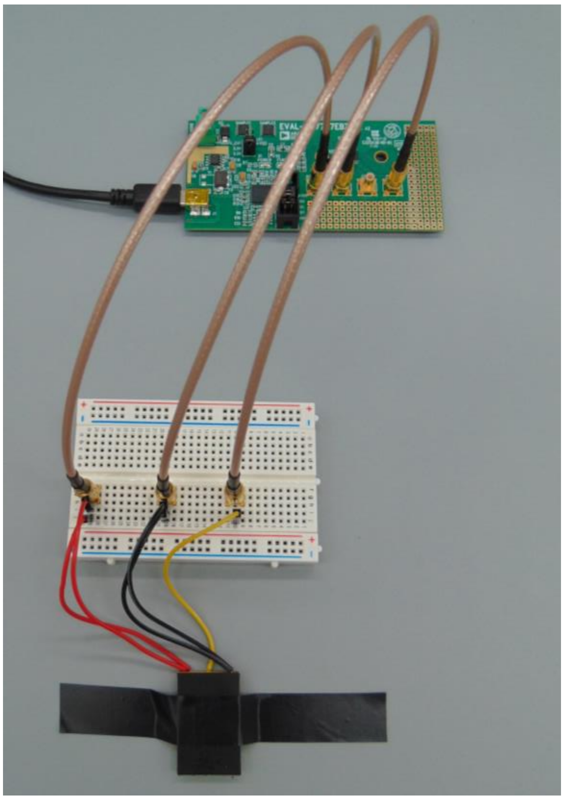

Figure 5: Experimental setup with the EVAL-AD7747 board (top) and the sensor (bottom).

Different Pins with a ranging length from 1 mm to 30 mm were put inside the sensor for the measurements. This is used to recreate a pin displacement. 100 measurements are taken for the capacitance for each pin length and for no pin. Fig. 6 shows three of the 30 pins.

Results

An experiment was conducted to compare the simulated capacitance with the measurement of the fabricated sensor. Fig. 7 shows the capacitance related to the pin length.

DOI 10.5162/sensoren2024/P29

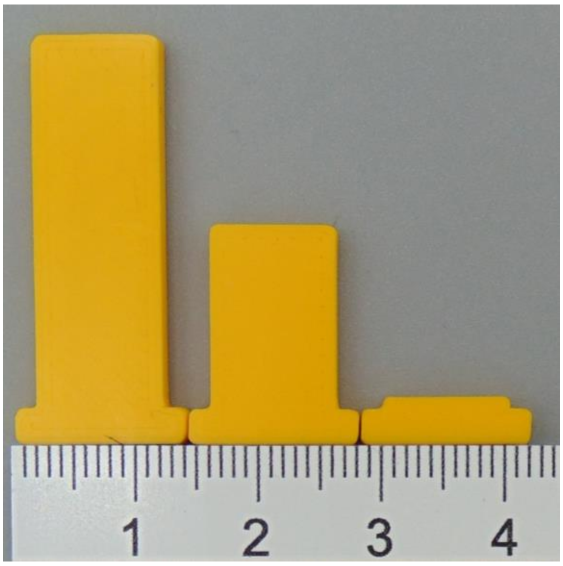

Figure 6: Pins for the experimental setup with a length of 30 mm (left), 15 mm (middle) and 1 mm (right).

The operating range of the sensing electrode starts at 5 mm and extends to 25 mm due to the sensor design. The measured values for the fabricated sensor have a standard deviation ranging from 6.2 fF to 55.6 fF.

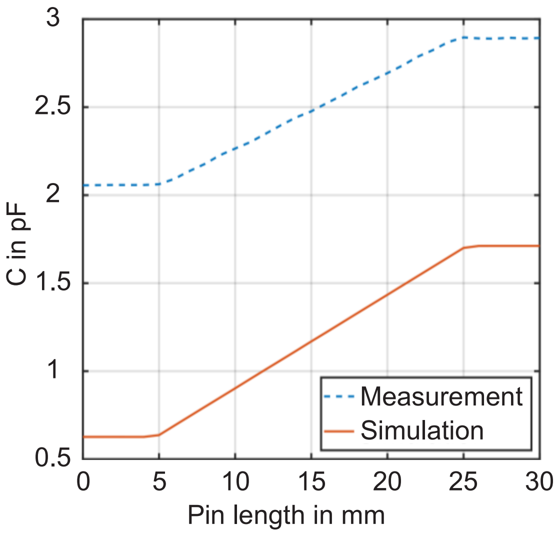

Figure 7: Simulated and measured capacitance of the sensor with different pin lengths.

Discussion

Fig. 7 shows an offset between the simulated and measured values of the sensor of 1.461 pF. The offset is due to the parasitic capacitance of the connecting wires, which were excluded from the simulation. The average deviation of the measured capacitance change between a displacement from 0 mm to 30 mm is 0.248 pF or 22.85%, compared to the simulation. This deviation mainly stems from deviating material parameters and geometric deviations due to manufacturing tolerances. The ε_r of 2.8 determined from other studies and used for the simulation does not appear to be correct in this case. There are different causes for the deviation: the different printer, filament, material batch, ambient conditions during production or the infill structure. With the exception of the pitch error related to the inaccurate ε_r, the measurements confirm the simulation. The sensor shows an approximately linear behavior in the relevant measurement area. Capacitance fluctuations at the edges of the sensing electrode due to fringing field effects could be minimized by applying guiding electrodes.

Conclusion

A capacitive displacement sensor concept for pin-gripper was designed, simulated, fabricated and evaluated. The sensor was manufactured using 3D printing, which opens up new design possibilities. This allows for the creation of complex components with integrated capacitive displacement sensors. The sensors can be scaled and customized for new applications. The experimental results confirm the simulation and the functionality of the fabricated sensor.

Future Work

The dielectric properties of PLA need to be studied in more detail to enable more accurate simulations. The effects of different geometries, materials other than PLA, and printing parameters such as layer height, infill pattern, or nozzle diameter will be the subject of future research.

A future research study will investigate real gripping scenarios using a scaled version of the sensor concept that consists of several pin sensors, as shown in Fig. 8.

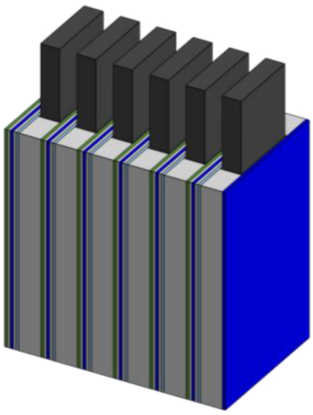

Figure 8: Scaled version of the sensor concept for further investigations.

Acknowledgement

Funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – 426605889

Literature

[1] J. Hernandez *et al.*, "Current Designs of Robotic Arm Grippers: A Comprehensive Systematic Review," *Robotics*, vol. 12, no. 1, Art. no. 1, Feb. 2023, doi: 10.3390/robotics12010005.

[2] P. Khadkotkar and A. K. Mishra, "Short Review on Gripper System: Introduction, Types and Applications," vol. 13, no. 2.

[3] A. Mo, H. Fu, and W. Zhang, "A Universal Gripper Base on Pivoted Pin Array with Chasing Tip: 11th International Conference, ICIRA 2018, Newcastle, NSW, Australia, August 9–11, 2018, Proceedings, Part II," 2018, pp. 100–111. doi: 10.1007/978-3-319-97589-4_9.

[4] W. Hasan, L. Gerez, and M. Liarokapis, "Model-Free, Vision-Based Object Identification and Contact Force Estimation with a Hyper-Adaptive Robotic Gripper," in *2020 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Las Vegas, NV, USA: IEEE, Oct. 2020, pp. 9514–9520. doi: 10.1109/IROS45743.2020.9340952.

[5] I. Kuzmanić, I. Vujović, M. Petković, and J. Šoda, "Influence of 3D printing properties on relative dielectric constant in PLA and ABS materials," *Prog Addit Manuf*, vol. 8, no. 4, pp. 703–710, Aug. 2023, doi: 10.1007/s40964-023-00411-0.

[6] C. Dichtl, P. Sippel, and S. Krohns, "Dielectric Properties of 3D Printed Polylactic Acid," *Advances in Materials Science and Engineering*, vol. 2017, p. e6913835, Jul. 2017, doi: 10.1155/2017/6913835.

[7] N. Hangst, S. Schroeder, T. M. Wendt, L. Stiglmeier, P. Gawron, and U. B. Himmelsbach, "Design of a Grounded Low-Cost Capacitive Liquid Level Sensor for Robotics Applications, especially in the Field of Gastronomy," in *Sensors and Measuring Systems; 21th ITG/GMA-Symposium*, May 2022, pp. 1–5.

[8] Analog Devices, "AD7747 24-Bit Capacitance-to-Digital Converter with Temperature Sensor Datasheet." 2007.